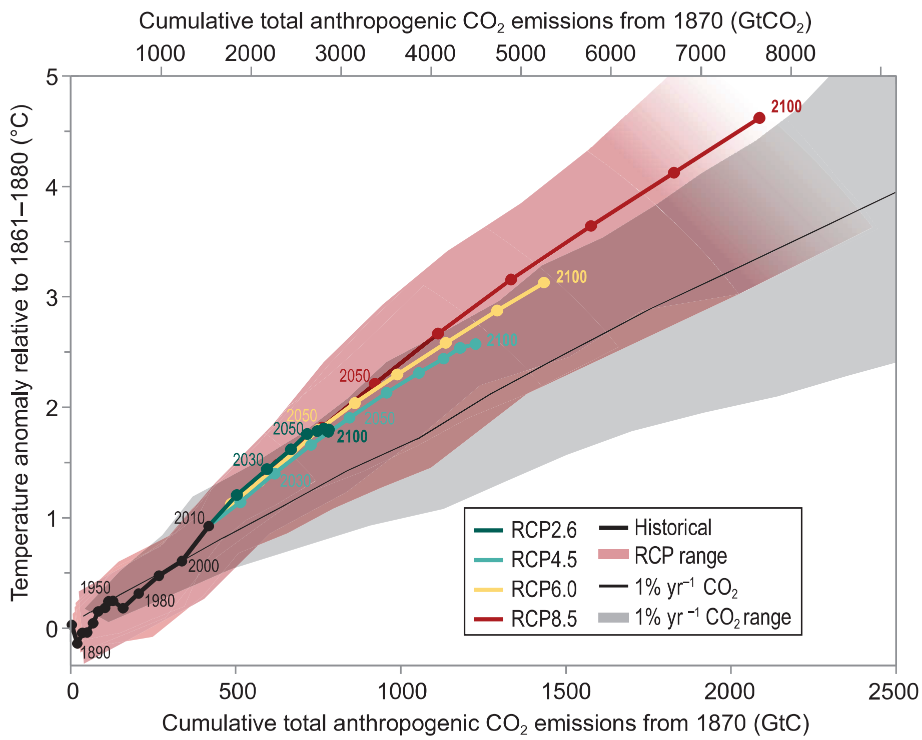

Figure 14.1: Global mean temperature change for a number of scenarios as a function of cumulative CO_2 emissions from preindustrial conditions, with time progressing along each individual line for each scenario. (Figure source: IPCC 2013;[42] ©IPCC. Used with permission).

Between 1870 and 2015, human activities, primarily the burning of fossil fuels and deforestation, emitted about 560 GtC in the form of CO_2 into the atmosphere.[20] According to best estimates in the literature, 1,000 GtC is the total cumulative amount of CO_2 that could be emitted yet still provide a two-thirds likelihood of preventing 3.6°F (2°C) of global mean warming since preindustrial times.[3, 21] That estimate, however, ignores the additional radiative forcing effects of non-CO_2 species (that is, the net positive forcing resulting from the forcing of other well-mixed GHGs, including halocarbons, plus the other ozone precursor gases and aerosols). Considering both historical and projected non-CO_2 effects reduces the estimated cumulative CO_2 budget compatible with any future warming goal,[18] and in the case of 3.6°F (2°C) it reduces the aforementioned estimate to 790 GtC.[3] Given this more comprehensive estimate, limiting the global average temperature increase to below 3.6°F (2°C) means approximately 230 GtC more CO_2 could be emitted globally. To illustrate, if one assumes future global emissions follow a pathway consistent with the lower scenario (RCP4.5), this cumulative carbon threshold is exceeded by around 2037, while under the higher scenario (RCP8.5) this occurs by around 2033. To limit the global average temperature increase to 2.7°F (1.5°C), the estimated cumulative CO_2 budget is about 590 GtC (assuming linear scaling with the compatible 3.6°F (2°C) budget that also considers non-CO_2 effects), meaning only about 30 GtC more of CO_2 could be emitted. Further emissions of 30 GtC (in the form of CO_2) are projected to occur in the next few years (Table 14.1).

Table 14.1: Dates illustrating when cumulative CO_2 emissions thresholds associated with eventual warming of 3.6°F or 2.7°F above preindustrial levels might be reached. RCP4.5 and RCP8.5 refer, respectively, to emissions consistent with the lower and higher scenarios used throughout this report. The estimated cumulative CO_2 emissions (measured in Gigatons (Gt) of carbon) associated with different probabilities (e.g., 66%) of preventing 3.6°F (2°C) of warming are from the IPCC.[3] The cumulative emissions compatible with 2.7°F (1.5°C) are linearly derived from the estimates associated with 3.6°F (2°C). The cumulative CO_2 estimates take into account the additional net warming effects associated with past and future non-CO_2 emissions consistent with the RCP scenarios. Historical CO_2 emissions from 1870–2015 (including fossil fuel combustion, land use change, and cement manufacturing) are from Le Quéré et al.[20] See Traceable Accounts for further details.

	Dates by when cumulative carbon emissions (GtC) since 1870 reach amount commensurate with 3.6°F (2°C), when accounting for non-CO_2 forcings		
	66% = 790 GtC	50% = 820 GtC	33% = 900 GtC
RCP4.5	2037	2040	2047
RCP8.5	2033	2035	2040
	Dates by when cumulative carbon emissions (GtC) since 1870 reach amount commensurate with 2.7°F (1.5°C), when accounting for non-CO_2 forcings		
	66% = 593 GtC	50% = 615 GtC	33% = 675 GtC
RCP4.5	2019	2021	2027
RCP8.5	2019	2021	2025

14.2 Pathways Centered Around 3.6°F (2°C)

The idea of a 3.6°F (2°C) goal can be found in the scientific literature as early as 1975. Nordhaus[22] justified it by simply stating, "If there were global temperatures more than 2 or 3°C above the current average temperature, this would take the climate outside of the range of observations which have been made over the last several hundred thousand years." Since that time, the concept of a 3.6°F (2°C) goal gained attention in both scientific and policy discourse. For example, the Stockholm Environment Institute[23] published a report stating that 3.6°F (2°C) "can be viewed as an upper limit beyond which the risks of grave damage to ecosystems, and of non-linear responses, are expected to increase rapidly." And in 2007, the IPCC Fourth Assessment Report stated, among other things: "Confidence has increased that a 1 to 2°C increase in global mean temperature above 1990 levels (about 1.5 to 2.5°C above pre-industrial) poses significant risks to many unique and threatened systems including many biodiversity hotspots." Most recently, the Paris Agreement of 2015 took on the long-term goal of "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels." Many countries announced GHG emissions reduction targets and related actions (formally called Intended Nationally Determined Contributions [INDCs]) in the lead up to the Paris meeting; these announcements addressed emissions through 2025 or 2030 and take a wide range of forms. A number of studies have generated projections of future GHG emissions based on these announcements and evaluated whether, if implemented, the resulting emissions reductions would limit the increase in global average temperatures to 3.6°F (2°C) above preindustrial levels. In June 2017, the United States announced its intent to withdraw from the Paris Agreement. The scenarios

assessed below were published prior to this announcement and therefore do not reflect the implications of this announcement.

Estimates of global emissions and temperature implications from emissions pathways consistent with targets and actions announced by governments in the lead up to the 2015 Paris climate conference[24, 25, 26, 27, 28] generally find that 1) these targets and actions would reduce GHG emissions growth by 2030 relative to a situation where these goals did not exist, though emissions are still not expected to be lower in 2030 than in 2015; and 2) the targets and actions would be a step towards limiting global mean temperature increase to 3.6°F (2°C), but by themselves, would be insufficient for this goal. According to one study, emissions pathways consistent with governments' announcements imply a median warming of 4.7°–5.6°F (2.6°–3.1°C) by 2100, though year 2100 temperature estimates depend on assumed emissions between 2030 and 2100.[24] For example, Climate Action Tracker,[26] using alternative post-2030 assumptions, put the range at 5.9°–7.0°F (3.3°–3.9°C).

Emissions pathways consistent with the targets and actions announced by governments in the lead up to the 2015 Paris conference have been evaluated in the context of the likelihood of global mean surface temperature change (Figure 14.2). It was found that the likelihood of limiting the global mean temperature increase to 3.6°F (2°C) or less was enhanced by these announced actions, but depended strongly on assumptions about subsequent policies and measures. Under a scenario in which countries maintain the same pace of decarbonization past 2030 as they announced in their first actions (leading up to 2025 or 2030) there is some likelihood (less than 10%) of preventing a global mean surface temperature change of 3.6°F (2°C) relative to preindustrial levels; this scenario thus holds open the possibility of achieving this goal, whereas there would be virtually no chance if emissions climbed to levels above those implied by country announcements (Figure 14.2).[27] Greater emissions reductions beyond 2030 (based on higher decarbonization rates past 2030) increase the likelihood of limiting warming to 3.6°F (2°C) or lower to about 30%, and almost eliminate the likelihood of a global mean temperature increase greater than 7°F (4°C). Scenarios that assume even greater emissions reductions past 2030 would be necessary to have at least a 50% probability of limiting warming to 3.6°F (2°C)[27] as discussed and illustrated further below.

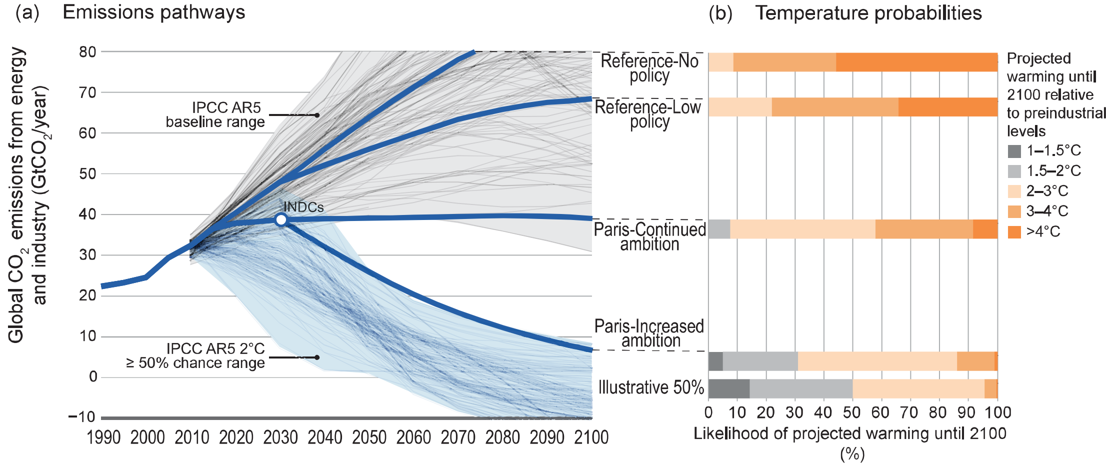

Figure 14.2: Global CO_2 emissions and probabilistic temperature outcomes of government announcements associated with the lead up to the Paris climate conference. (a) Global CO_2 emissions from energy and industry (includes CO_2 emissions from all fossil fuel production and use and industrial processes such as cement manufacture that also produce CO_2 as a byproduct) for emissions pathways following no policy, current policy, meeting the governments' announcements with constant country decarbonization rates past 2030, and meeting the governments' announcements with higher rates of decarbonization past 2030. INDCs refer to Intended Nationally Determined Contributions which is the term used for the governments' announced actions in the lead up to Paris. (b) Likelihoods of different levels of increase in global mean surface temperature during the 21st century relative to preindustrial levels for the four scenarios. Although (a) shows only CO_2 emissions from energy and industry, temperature outcomes are based on the full suite of GHG, aerosol, and short-lived species emissions across the full set of human activities and physical Earth systems. (Figure source: Fawcett et al. 2015[27]).

There is a limited range of pathways which enable the world to remain below 3.6°F (2°C) of warming (see Figure 14.3), and almost all but the most rapid near-term mitigation pathways are heavily reliant on the implementation of CO_2 removal from the atmosphere later in the century or other climate intervention, discussed below. If global emissions are in line with the first round of announced government actions by 2030, then the world likely needs to reduce effective GHG emissions to zero by 2080 and be significantly net negative by the end of the century (relying on as yet unproven technologies to remove GHGs from the atmosphere) in order to stay below 3.6°F (2°C) of warming. Avoiding 2.7°F (1.5°C) of warming requires more aggressive action still, with net zero emissions achieved by 2050 and net negative emissions thereafter. In either case, faster near-term emissions reductions significantly decrease the requirements for net negative emissions in the future.

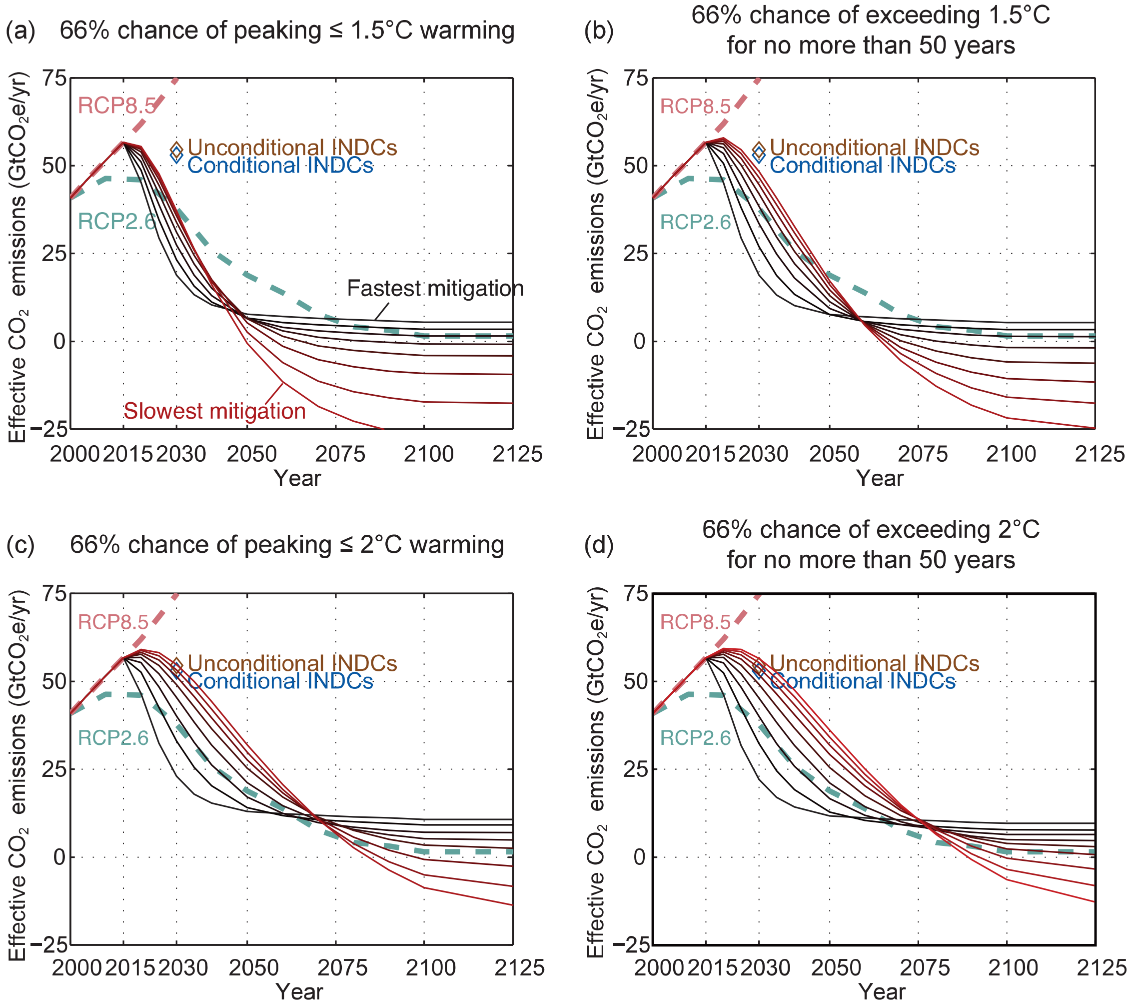

Figure 14.3: Global emissions pathways for GHGs, expressed as CO_2-equivalent emissions, which would be consistent with different temperature goals (relative to preindustrial temperatures). INDCs refer to Intended Nationally Determined Contributions which is the term used for the governments' announced actions in the lead up to Paris. (a) shows a set of pathways where global mean temperatures would likely (66%) not exceed 2.7°F (1.5°C). A number of pathways are consistent with the goal, ranging from the red curve (slowest near-term mitigation with large negative emissions requirements in the future) to the black curve with rapid near-term mitigation and less future negative emissions. (b) shows similar pathways with a 66% chance of exceeding 2.7°F (1.5°C) for only 50 years, where (c) and (d) show similar emission pathways for 3.6°F (2°C). (Figure source: Sanderson et al. 2016[25]).

14.3 The Potential Role of Climate Intervention in Mitigation Strategies

Limiting the global mean temperature increase through emissions reductions or adapting to the impacts of a greater-than-3.6°F (2°C) warmer world have been acknowledged as severely challenging tasks by the international science and policy communities. Consequently, there is increased interest by some scientists and policy makers in exploring additional measures designed to reduce net radiative forcing through other, as yet untested actions, which are often referred to as geoengineering or climate intervention (CI) actions. CI approaches are generally divided into two categories: carbon dioxide removal (CDR)[29] and solar radiation management (SRM).[30] CDR and SRM methods may have future roles in helping meet global temperature goals. Both methods would reduce global average temperature by reducing net global radiative forcing: CDR through reducing atmospheric CO_2 concentrations and SRM through increasing Earth's albedo.

The evaluation of the suitability and advisability of potential CI actions requires a decision framework that includes important dimensions beyond scientific and technical considerations. Among these dimensions to be considered are the potential development of global and national governance and oversight procedures, geopolitical relations, legal considerations, environmental, economic and societal impacts, ethical considerations, and the relationships to global climate policy and current GHG mitigation and adaptation actions. It is clear that these social science and other non-physical science dimensions are likely to be a major part of the decision framework and ultimately control the adoption and effectiveness of CI actions. This report only acknowledges these mostly non-physical scientific dimensions and must forego a detailed discussion.

By removing CO_2 from the atmosphere, CDR directly addresses the principal cause of climate change. Potential CDR approaches include direct air capture, currently well-understood biological methods on land (for example, afforestation), less well-understood and potentially risky methods in the ocean (for example, ocean fertilization), and accelerated weathering (for example, forming calcium carbonate on land or in the oceans).[29] While CDR is technically possible, the primary challenge is achieving the required scale of removal in a cost-effective manner, which in part presumes a comparison to the costs of other, more traditional GHG mitigation options.[31, 32] In principle, at large scale, CDR could measurably reduce CO_2 concentrations (that is, cause negative emissions). Point-source capture (as opposed to CO_2 capture from ambient air) and removal of CO_2 is a particularly effective CDR method. The climate value of avoided CO_2 emissions is essentially equivalent to that of the atmospheric removal of the same amount. To realize sustained climate benefits from CDR, however, the removal of CO_2 from the atmosphere must be essentially permanent—at least several centuries to millennia. In addition to high costs, CDR has the additional limitation of long implementation times.

By contrast, SRM approaches offer the only known CI methods of cooling Earth within a few years after inception. An important limitation of SRM is that it would not address damage to ocean ecosystems from increasing ocean acidification due to continued CO_2 uptake. SRM could theoretically have a significant global impact even if implemented by a small number of nations, and by nations that are not also the major emitters of GHGs; this could be viewed either as a benefit or risk of SRM.[30]

Proposed SRM concepts increase Earth's albedo through injection of sulfur gases or aerosols into the stratosphere (thereby simulating

the effects of explosive volcanic eruptions) or marine cloud brightening through aerosol injection near the ocean surface. Injection of solid particles is an alternative to sulfur and yet other SRM methods could be deployed in space. Studies have evaluated the expected effort and effectiveness of various SRM methods.[30, 33] For example, model runs were performed in the GeoMIP project using the full CMIP5 model suite to illustrate the effect of reducing top-of-the-atmosphere insolation to offset climate warming from CO_2.[34] The idealized runs, which assumed an abrupt, globally-uniform insolation reduction in a $4 \times CO_2$ atmosphere, show that temperature increases are largely offset, most sea ice loss is avoided, average precipitation changes are small, and net primary productivity increases. However, important regional changes in climate variables are likely in SRM scenarios as discussed below.

As global ambitions increase to avoid or remove CO_2 emissions, probabilities of large increases in global temperatures by 2100 are proportionately reduced.[27] Scenarios in which large-scale CDR is used to meet a 3.6°F (2°C) limit while allowing business-as-usual consumption of fossil fuels are likely not feasible with present technologies. Model SRM scenarios have been developed that show reductions in radiative forcing up to 1 W/m^2 with annual stratospheric injections of 1 Mt of sulfur from aircraft or other platforms.[35, 36] Preliminary studies suggest that this could be accomplished at an implementation cost as low as a few billion dollars per year using current technology, enabling an individual country or subnational entity to conduct activities having significant global climate impacts.

SRM scenarios could in principle be designed to follow a particular radiative forcing trajectory, with adjustments made in response to monitoring of the climate effects.[37] SRM could be used as an interim measure to avoid peaks in global average temperature and other climate parameters. The assumption is often made that SRM measures, once implemented, must continue indefinitely in order to avoid the rapid climate change that would occur if the measures were abruptly stopped. SRM could be used, however, as an interim measure to buy time for the implementation of emissions reductions and/or CDR, and SRM could be phased out as emissions reductions and CDR are phased in, to avoid abrupt changes in radiative forcing.[37]

SRM via marine cloud brightening derives from changes in cloud albedo from injection of aerosols into low-level clouds, primarily over the oceans. Clouds with smaller and more numerous droplets reflect more sunlight than clouds with fewer and larger droplets. Current models provide more confidence in the effects of stratospheric injection than in marine cloud brightening and in achieving scales large enough to reduce global forcing.[30]

CDR and SRM have substantial uncertainties regarding their effectiveness and unintended consequences. For example, CDR on a large scale may disturb natural systems and have important implications for land-use changes. For SRM actions, even if the reduction in global average radiative forcing from SRM was exactly equal to the radiative forcing from GHGs, the regional and temporal patterns of these forcings would have important differences. While SRM could rapidly lower global mean temperatures, the effects on precipitation patterns, light availability, crop yields, acid rain, pollution levels, temperature gradients, and atmospheric circulation in response to such actions are less well understood. Also, the reduction in sunlight from SRM may have effects on agriculture and ecosystems. In general, restoring regional preindustrial temperature and precipitation conditions through

SRM actions is not expected to be possible based on ensemble modeling studies.[38] As a consequence, optimizing the climate and geopolitical value of SRM actions would likely involve tradeoffs between regional temperature and precipitation changes.[39] Alternatively, intervention options have been proposed to address particular regional impacts.[40]

GHG forcing has the potential to push the climate farther into unprecedented states for human civilization and increase the likelihood of "surprises" (see Ch. 15: Potential Surprises). CI could prevent climate change from reaching a state with more unpredictable consequences. The potential for rapid changes upon initiation (or ceasing) of a CI action would require adaptation on timescales significantly more rapid than what would otherwise be necessary. The NAS[29, 30] and the Royal Society[41] recognized that research on the feasibilities and consequences of CI actions is incomplete and call for continued research to improve knowledge of the feasibility, risks, and benefits of CI techniques.

TRACEABLE ACCOUNTS

Key Finding 1

Reducing net emissions of CO_2 is necessary to limit near-term climate change and long-term warming. Other greenhouse gases (for example, methane) and black carbon aerosols exert stronger warming effects than CO_2 on a per ton basis, but they do not persist as long in the atmosphere; therefore, mitigation of non-CO_2 species contributes substantially to near-term cooling benefits but cannot be relied upon for ultimate stabilization goals. (*Very high confidence*)

Description of evidence base

Joos et al.[2] and Ciais et al. (see Box 6.1 in particular)[1] describe the climate response of CO_2 pulse emissions, and Solomon et al.,[4] NRC,[19] and Collins et al.[3] describe the long-term warming and other climate effects associated with CO_2 emissions. Paltsev et al.[8] and Collins et al.[3] describe the near-term vs. long-term nature of climate outcomes resulting from GHG mitigation. Myhre et al.[11] synthesize numerous studies detailing information about the radiative forcing effects and atmospheric lifetimes of all GHGs and aerosols (see in particular Appendix 8A therein). A recent body of literature has emerged highlighting the particular role that non-CO_2 mitigation can play in providing near-term cooling benefits (e.g., Shindell et al. 2012;[17] Zaelke and Borgford-Parnell 2015;[10] Rogelj et al. 2015[18]). For each of the individual statements made in Key Finding 1, there are numerous literature sources that provide consistent grounds on which to make these statements with *very high confidence*.

Major uncertainties

The Key Finding is comprised of qualitative statements that are traceable to the literature described above and in this chapter. Uncertainties affecting estimates of the exact timing and magnitude of the climate response following emissions (or avoidance of those emissions) of CO_2 and other GHGs involve the quantity of emissions, climate sensitivity, some uncertainty about the removal time or atmospheric lifetime of CO_2 and other GHGs, and the choice of model carrying out future simulations. The role of black carbon in climate change is more uncertain compared to the role of the well-mixed GHGs (see Bond et al. 2013[12]).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Key Finding 1 is comprised of qualitative statements based on a body of literature for which there is a high level of agreement. There is a well-established understanding, based in the literature, of the atmospheric lifetime and warming effects of CO_2 vs. other GHGs after emission, and in turn how atmospheric concentration levels respond following the emission of CO_2 and other GHGs.

Summary sentence or paragraph that integrates the above information

The qualitative statements contained in Key Finding 1 reflect aspects of fundamental scientific understanding, well grounded in the literature, that provide a relevant framework for considering the role of CO_2 and non-CO_2 species in mitigating climate change.

Key Finding 2

Stabilizing global mean temperature to less than 3.6°F (2°C) above preindustrial levels requires substantial reductions in net global CO_2 emissions prior to 2040 relative to present-day values and likely requires net emissions to become zero or possibly negative later in the century. After accounting for the temperature effects of non-CO_2 species, cumulative global CO_2 emissions must stay below about 800 GtC in order to provide a two-thirds likelihood of preventing 3.6°F (2°C) of warming. Given estimated cumulative emissions since 1870, no more than approximately 230 GtC may be emitted in the future to remain under this temperature threshold. Assuming global emissions are equal to or greater than those consistent with the RCP4.5 scenario, this cumulative carbon threshold would be exceeded in approximately two decades. (*High confidence*)

Description of evidence base

Key Finding 2 is a case study, focused on a pathway associated with 3.6°F (2°C) of warming, based on the more general concepts described in the chapter. As such, the

evidence for the relationship between cumulative CO_2 emissions and global mean temperature response[3, 19, 21] also supports Key Finding 3.

Numerous studies have provided best estimates of cumulative CO_2 compatible with 3.6°F (2°C) of warming above preindustrial levels, including a synthesis by the IPCC.[3] Sanderson et al.[25] provide further recent evidence to support the statement that net CO_2 emissions would need to approach zero or become negative later in the century in order to avoid this level of warming. Rogelj et al. 2015[18] and the IPCC[3] demonstrate that the consideration of non-CO_2 species has the effect of further constraining the amount of cumulative CO_2 emissions compatible with 3.6°F (2°C) of warming.

Table 14.1 shows the IPCC estimates associated with different probabilities (66% [the one highlighted in Key Finding 2], 50%, and 33%) of cumulative CO_2 emissions compatible with warming of 3.6°F (2°C) above preindustrial levels, and the cumulative CO_2 emissions compatible with 2.7°F (1.5°C) are in turn linearly derived from those, based on the understanding that cumulative emissions scale linearly with global mean temperature response. The IPCC estimates take into account the additional radiative forcing effects—past and future—of non-CO_2 species based on the emissions pathways consistent with the RCP scenarios (available here: https://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=about#descript).

The authors calculated the dates shown in Table 14.1, which supports the last statement in Key Finding 2, based on Le Quéré et al.[20] and the publicly available RCP database. Le Quéré et al.[20] provide the widely used reference for historical global, annual CO_2 emissions from 1870 to 2015 (land-use change emissions were estimated up to year 2010 so are assumed to be constant between 2010 and 2015). Future CO_2 emissions are based on the lower and higher scenarios (RCP4.5 and RCP8.5, respectively); annual numbers between model-projected years (2020, 2030, 2040, etc.) are linearly interpolated.

Major uncertainties

There are large uncertainties about the course of future CO_2 and non-CO_2 emissions, but the fundamental point that CO_2 emissions need to eventually approach zero or possibly become net negative to stabilize warming below 3.6°F (2°C) holds regardless of future emissions scenario. There are also large uncertainties about the magnitude of past (since 1870 in this case) CO_2 and non-CO_2 emissions, which in turn influence the uncertainty about compatible cumulative emissions from the present day forward. Further uncertainties regarding non-CO_2 species, including aerosols, include their radiative forcing effects. The uncertainty in achieving the temperature targets for a given emissions pathway is, in large part, reflected by the range of probabilities shown in Table 14.1.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is *very high* confidence in the first statement of Key Finding 2 because it is based on a number of sources with a high level of agreement. The role of non-CO_2 species in particular introduces uncertainty in the second statement of Key Finding 2 regarding compatible cumulative CO_2 emissions that take into account past and future radiative forcing effects of non-CO_2 species; though this estimate is based on a synthesis of numerous studies by the IPCC. The last statement of Key Finding 2 is straightforward based on the best available estimates of historical emissions in combination with the widely used future projections of the RCP scenarios.

Summary sentence or paragraph that integrates the above information

Fundamental scientific understanding of the climate system provides a framework for considering potential pathways for achieving a target of preventing 3.6°F (2°C) of warming. There are uncertainties about cumulative CO_2 emissions compatible with this goal, in large part because of uncertainties about the role of non-CO_2 species, but it appears, based on past emissions and future projections, that the cumulative carbon threshold for this goal could be reached or exceeded in about two decades.

Key Finding 3

Achieving global greenhouse gas emissions reductions before 2030 consistent with targets and actions announced by governments in the lead up to the 2015 Paris climate conference would hold open the possibility of meeting the long-term temperature goal of limiting global warming to 3.6°F (2°C) above preindustrial levels, whereas there would be virtually no chance if global net emissions followed a pathway well above those implied by country announcements. Actions in the announcements are, by themselves, insufficient to meet a 3.6°F (2°C) goal; the likelihood of achieving that goal depends strongly on the magnitude of global emissions reductions after 2030. (*High confidence*)

Description of evidence base

The primary source supporting this key finding is Fawcett et al.;[27] it is also supported by Rogelj et al.,[24] Sanderson et al.,[25] and the Climate Action Tracker.[26] Each of these analyses evaluated the global climate implications of the aggregation of the individual country contributions thus far put forward under the Paris Agreement.

Major uncertainties

The largest uncertainty lies in the assumption of achieving emissions reductions consistent with the announcements prior to December 2015; these reductions are assumed to be achieved but could either be over- or underachieved. This in turn creates uncertainty about the extent of emissions reductions that would be needed after the first round of government announcements in order to achieve the 2°C or any other target. The response of the climate system, the climate sensitivity, is also a source of uncertainty; the Fawcett et al. analysis used the IPCC AR5 range, 1.5° to 4.5°C.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is *high* confidence in this key finding because a number of analyses have examined the implications of these announcements and have come to similar conclusions, as captured in this key finding.

Summary sentence or paragraph that integrates the above information

Different analyses have estimated the implications for global mean temperature of the emissions reductions consistent with the actions announced by governments in the lead up to the 2015 Paris climate conference and have reached similar conclusions. Assuming emissions reductions indicated in these announcements are achieved, along with a range of climate sensitivities, these contributions provide some likelihood of meeting the long-term goal of limiting global warming to well below 3.6°F (2°C) above preindustrial levels, but much depends on assumptions about what happens after 2030.

Key Finding 4

Further assessments of the technical feasibilities, costs, risks, co-benefits, and governance challenges of climate intervention or geoengineering strategies, which are as yet unproven at scale, are a necessary step before judgments about the benefits and risks of these approaches can be made with high confidence. (*High confidence*)

Description of evidence base

Key Finding 4 contains qualitative statements based on the growing literature addressing this topic, including from such bodies as the National Academy of Sciences and the Royal Society, coupled with judgment by the authors about the future interest level in this topic.

Major uncertainties

The major uncertainty is how public perception and interest among policymakers in climate intervention may change over time, even independently from the perceived level of progress made towards reducing CO_2 and other GHG emissions over time.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is *high* confidence that climate intervention strategies may gain greater attention, especially if efforts to slow the buildup of atmospheric CO_2 and other GHGs are considered inadequate by many in the scientific and policy communities.

Summary sentence or paragraph that integrates the above information

The key finding is a qualitative statement based on the growing literature on this topic. The uncertainty moving forward is the comfort level and desire among numerous stakeholders to research and potentially carry out these climate intervention strategies, particularly in light of how progress by the global community to reduce GHG emissions is perceived.

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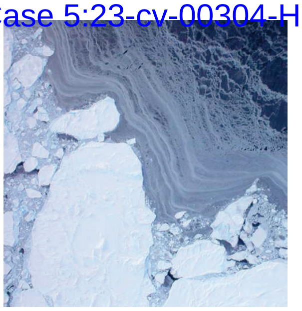

15

Potential Surprises: Compound Extremes and Tipping Elements

KEY FINDINGS

1. Positive feedbacks (self-reinforcing cycles) within the climate system have the potential to accelerate human-induced climate change and even shift the Earth's climate system, in part or in whole, into new states that are very different from those experienced in the recent past (for example, ones with greatly diminished ice sheets or different large-scale patterns of atmosphere or ocean circulation). Some feedbacks and potential state shifts can be modeled and quantified; others can be modeled or identified but not quantified; and some are probably still unknown. (*Very high confidence* in the potential for state shifts and in the incompleteness of knowledge about feedbacks and potential state shifts).

2. The physical and socioeconomic impacts of compound extreme events (such as simultaneous heat and drought, wildfires associated with hot and dry conditions, or flooding associated with high precipitation on top of snow or waterlogged ground) can be greater than the sum of the parts (*very high confidence*). Few analyses consider the spatial or temporal correlation between extreme events.

3. While climate models incorporate important climate processes that can be well quantified, they do not include all of the processes that can contribute to feedbacks, compound extreme events, and abrupt and/or irreversible changes. For this reason, future changes outside the range projected by climate models cannot be ruled out (*very high confidence*). Moreover, the systematic tendency of climate models to underestimate temperature change during warm paleoclimates suggests that climate models are more likely to underestimate than to overestimate the amount of long-term future change (*medium confidence*).

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15.1 Introduction

The Earth system is made up of many components that interact in complex ways across a broad range of temporal and spatial scales. As a result of these interactions the behavior of the system cannot be predicted by looking at individual components in isolation. Negative feedbacks, or self-stabilizing cycles, within and between components of the Earth system can dampen changes (Ch. 2: Physical Drivers of Climate Change). However, their stabilizing effects render such feedbacks of less concern from a risk perspective than positive feedbacks, or self-reinforcing cycles. Positive feedbacks magnify both natural and anthropogenic changes. Some Earth system components, such as arctic sea ice and the polar ice sheets, may exhibit thresholds beyond which these self-reinforcing cycles can drive the component, or the entire system, into a radically different state. Although the probabilities of these state shifts may be difficult to assess, their consequences could be high, potentially exceeding anything anticipated by climate model projections for the coming century.

Humanity's effect on the Earth system, through the large-scale combustion of fossil fuels and widespread deforestation and the resulting release of carbon dioxide (CO_2) into the atmosphere, as well as through emissions of other greenhouse gases and radiatively active substances from human activities, is unprecedented (Ch. 2: Physical Drivers of Climate Change). These forcings are driving changes in temperature and other climate variables. Previous chapters have covered a variety of observed and projected changes in such variables, including averages and extremes of temperature, precipitation, sea level, and storm events (see Chapters 1, 4–13).

While the distribution of climate model projections provides insight into the range of possible future changes, this range is limited by the fact that models do not include or fully represent all of the known processes and components of the Earth system (e.g., ice sheets or arctic carbon reservoirs),[1] nor do they include all of the interactions between these components that contribute to the self-stabilizing and self-reinforcing cycles mentioned above (e.g., the dynamics of the interactions between ice sheets, the ocean, and the atmosphere). They also do not include currently unknown processes that may become increasingly relevant under increasingly large climate forcings. This limitation is emphasized by the systematic tendency of climate models to underestimate temperature change during warm paleoclimates (Section 15.5). Therefore, there is significant potential for humanity's effect on the planet to result in unanticipated surprises and a broad consensus that the further and faster the Earth system is pushed towards warming, the greater the risk of such surprises.

Scientists have been surprised by the Earth system many times in the past. The discovery of the ozone hole is a clear example. Prior to groundbreaking work by Molina and Rowland[2], chlorofluorocarbons (CFCs) were viewed as chemically inert; the chemistry by which they catalyzed stratospheric ozone depletion was unknown. Within eleven years of Molina and Rowland's work, British Antarctic Survey scientists reported ground observations showing that spring ozone concentrations in the Antarctic, driven by chlorine from human-emitted CFCs, had fallen by about one-third since the late 1960s.[3] The problem quickly moved from being an "unknown unknown" to a "known known," and by 1987, the Montreal Protocol was adopted to phase out these ozone-depleting substances.

Another surprise has come from arctic sea ice. While the potential for powerful positive ice-albedo feedbacks has been understood since the late 19th century, climate models

have struggled to capture the magnitude of these feedbacks and to include all the relevant dynamics that affect sea ice extent. As of 2007, the observed decline in arctic sea ice from the start of the satellite era in 1979 outpaced the declines projected by almost all the models used by the Intergovernmental Panel on Climate Change's Fourth Assessment Report (AR4),[4] and it was not until AR4 that the IPCC first raised the prospect of an ice-free summer Arctic during this century.[5] More recent studies are more consistent with observations and have moved the date of an ice-free summer Arctic up to approximately mid-century (see Ch. 11: Arctic Changes).[6] But continued rapid declines—2016 featured the lowest annually averaged arctic sea ice extent on record, and the 2017 winter maximum was also the lowest on record—suggest that climate models may still be underestimating or missing relevant feedback processes. These processes could include, for example, effects of melt ponds, changes in storminess and ocean wave impacts, and warming of near surface waters.[7, 8, 9]

This chapter focuses primarily on two types of potential surprises. The first arises from potential changes in correlations between extreme events that may not be surprising on their own but together can increase the likelihood of compound extremes, in which multiple events occur simultaneously or in rapid sequence. Increasingly frequent compound extremes—either of multiple types of events (such as paired extremes of droughts and intense rainfall) or over greater spatial or temporal scales (such as a drought occurring in multiple major agricultural regions around the world or lasting for multiple decades)—are often not captured by analyses that focus solely on one type of extreme.

The second type of surprise arises from self-reinforcing cycles, which can give rise to "tipping elements"—subcomponents of the Earth system that can be stable in multiple different states and can be "tipped" between these states by small changes in forcing, amplified by positive feedbacks. Examples of potential tipping elements include ice sheets, modes of atmosphere–ocean circulation like the El Niño–Southern Oscillation, patterns of ocean circulation like the Atlantic meridional overturning circulation, and large-scale ecosystems like the Amazon rainforest.[10, 11] While compound extremes and tipping elements constitute at least partially "known unknowns," the paleoclimate record also suggests the possibility of "unknown unknowns." These possibilities arise in part from the tendency of current climate models to underestimate past responses to forcing, for reasons that may or may not be explained by current hypotheses (e.g., hypotheses related to positive feedbacks that are unrepresented or poorly represented in existing models).

15.2 Risk Quantification and Its Limits

Quantifying the risk of low-probability, high-impact events, based on models or observations, usually involves examining the tails of a probability distribution function (PDF). Robust detection, attribution, and projection of such events into the future is challenged by multiple factors, including an observational record that often does not represent the full range of physical possibilities in the climate system, as well as the limitations of the statistical tools, scientific understanding, and models used to describe these processes.[12]

The 2013 Boulder, Colorado, floods and the Dust Bowl of the 1930s in the central United States are two examples of extreme events whose magnitude and/or extent are unprecedented in the observational record. Statistical approaches such as Extreme Value Theory can be used to model and estimate the magnitude of rare events that may not have occurred in the observational record, such as the "1,000-

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year flood event" (i.e., a flood event with a 0.1% chance of occurrence in any given year) (e.g., Smith 1987[13]). While useful for many applications, these are not physical models: they are statistical models that are typically based on the assumption that observed patterns of natural variability (that is, the sample from which the models derive their statistics) are both valid and stationary beyond the observational period. Extremely rare events can also be assessed based upon paleoclimate records and physical modeling. In the paleoclimatic record, numerous abrupt changes have occurred since the last deglaciation, many larger than those recorded in the instrumental record. For example, tree ring records of drought in the western United States show abrupt, long-lasting megadroughts that were similar to but more intense and longer-lasting than the 1930s Dust Bowl.[14]

Since models are based on physics rather than observational data, they are not inherently constrained to any given time period or set of physical conditions. They have been used to study the Earth in the distant past and even the climate of other planets (e.g., Lunt et al. 2012;[15] Navarro et al. 2014[16]). Looking to the future, thousands of years' worth of simulations can be generated and explored to characterize small-probability, high-risk extreme events, as well as correlated extremes (see Section 15.3). However, the likelihood that such model events represent real risks is limited by well-known uncertainties in climate modeling related to parameterizations, model resolution, and limits to scientific understanding (Ch. 4: Projections). For example, conventional convective parameterizations in global climate models systematically underestimate extreme precipitation.[17] In addition, models often do not accurately capture or even include the processes, such as permafrost feedbacks, by which abrupt, non-reversible change may occur (see Section 15.4). An analysis focusing on physical climate predictions over the last 20 years found a tendency for scientific assessments such as those of the IPCC to under-predict rather than over-predict changes that were subsequently observed.[18]

15.3 Compound Extremes

An important aspect of surprise is the potential for compound extreme events. These can be events that occur at the same time or in sequence (such as consecutive floods in the same region) and in the same geographic location or at multiple locations within a given country or around the world (such as the 2009 Australian floods and wildfires). They may consist of multiple extreme events or of events that by themselves may not be extreme but together produce a multi-event occurrence (such as a heat wave accompanied by drought[19]). It is possible for the net impact of these events to be less than the sum of the individual events if their effects cancel each other out. For example, increasing CO_2 concentrations and acceleration of the hydrological cycle may mitigate the future impact of extremes in gross primary productivity that currently impact the carbon cycle.[20] However, from a risk perspective, the primary concern relates to compound extremes with additive or even multiplicative effects.

Some areas are susceptible to multiple types of extreme events that can occur simultaneously. For example, certain regions are susceptible to both flooding from coastal storms and riverine flooding from snow melt, and a compound event would be the occurrence of both simultaneously. Compound events can also result from shared forcing factors, including natural cycles like the El Niño–Southern Oscillation (ENSO); large-scale circulation patterns, such as the ridge observed during the 2011–2017 California drought (e.g., Swain et al. 2016[21]; see also Ch. 8: Droughts, Floods, and Wildfires); or relatively greater regional sensitivity

to global change, as may occur in "hot spots" such as the western United States.[22] Finally, compound events can result from mutually reinforcing cycles between individual events, such as the relationship between drought and heat, linked through soil moisture and evaporation, in water-limited areas.[23]

In a changing climate, the probability of compound events can be altered if there is an underlying trend in conditions such as mean temperature, precipitation, or sea level that alters the baseline conditions or vulnerability of a region. It can also be altered if there is a change in the frequency or intensity of individual extreme events relative to the changing mean (for example, stronger storm surges, more frequent heat waves, or heavier precipitation events).

The occurrence of warm/dry and warm/wet conditions is discussed extensively in the literature; at the global scale, these conditions have increased since the 1950s,[24] and analysis of NOAA's billion-dollar disasters illustrates the correlation between temperature and precipitation extremes during the costliest climate and weather events since 1980 (Figure 15.1, right). In the future, hot summers will become more frequent, and although it is not always clear for every region whether drought frequency will change, droughts in already dry regions, such as the southwestern United States, are likely to be more intense in a warmer world due to faster evaporation and associated surface drying.[25, 26, 27] For other regions, however, the picture is not as clear. Recent examples of heat/drought events (in the southern Great Plains in 2011 or in California, 2012–2016) have highlighted the inadequacy of traditional univariate risk assessment methods.[28] Yet a bivariate analysis for the contiguous United States of precipitation deficits and positive temperature anomalies finds no significant trend in the last 30 years.[29]

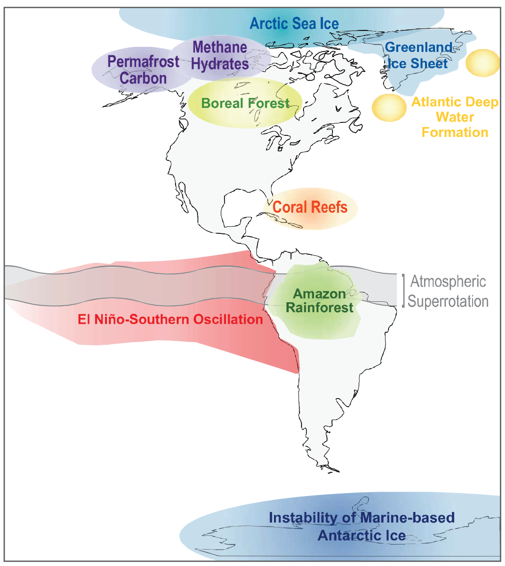
Another compound event frequently discussed in the literature is the increase in wildfire risk resulting from the combined effects of high precipitation variability (wet seasons followed by dry), elevated temperature, and low humidity. If followed by heavy rain, wildfires can in turn increase the risk of landslides and erosion. They can also radically increase emissions of greenhouse gases, as demonstrated by the amount of carbon dioxide produced by the Fort McMurray fires of May 2016—more than 10% of Canada's annual emissions.

A third example of a compound event involves flooding arising from wet conditions due to precipitation or to snowmelt, which could be exacerbated by warm temperatures. These wet conditions lead to high groundwater levels, saturated soils, and/or elevated river flows, which can increase the risk of flooding associated with a given storm days or even months later.[23]

Compound events may surprise in two ways. The first is if known types of compound events recur, but are stronger, longer-lasting, and/or more widespread than those experienced in the observational record or projected by model simulations for the future. One example would be simultaneous drought events in different agricultural regions across the country, or even around the world, that challenge the ability of human systems to provide adequate affordable food. Regions that lack the ability to adapt would be most vulnerable to this risk (e.g., Fraser et al. 2013[30]). Another example would be the concurrent and more severe heavy precipitation events that have occurred in the U.S. Midwest in recent years. After record insurance payouts following the events, in 2014 several insurance companies, led by Farmers Insurance, sued the city of Chicago and surrounding counties for failing to adequately prepare for the impacts of a changing climate. Although the suit was

dropped later that same year, their point was made: in some regions of the United States, the insurance industry is not able to cope with the increasing frequency and/or concurrence of certain types of extreme events.

The second way in which compound events could surprise would be the emergence of new types of compound events not observed in the historical record or predicted by model simulations, due to model limitations (in terms of both their spatial resolution as well as their ability to explicitly resolve the physical processes that would result in such compound events), an increase in the frequency of such events from human-induced climate change, or both. An example is Hurricane Sandy, where sea level rise, anomalously high ocean temperatures, and high tides combined to strengthen both the storm and the magnitude of the associated storm surge.[31] At the same time, a blocking ridge over Greenland—a feature whose strength and frequency may be related to both Greenland surface melt and reduced summer sea ice in the Arctic (see also Ch. 11: Arctic Changes)[32]—redirected the storm inland to what was, coincidentally, an exceptionally high-exposure location.



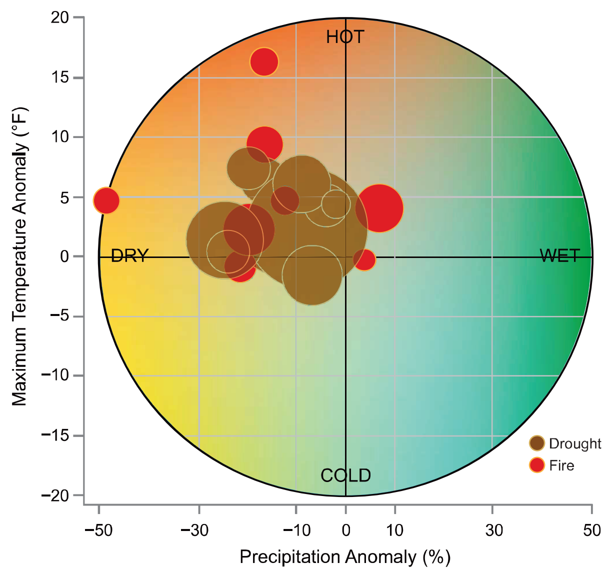


Figure 15.1: (left) Potential climatic tipping elements affecting the Americas (Figure source: adapted from Lenton et al. 2008[10]). (right) Wildfire and drought events from the NOAA Billion Dollar Weather Events list (1980–2016), and associated temperature and precipitation anomalies. Dot size scales with the magnitude of impact, as reflected by the cost of the event. These high-impact events occur preferentially under hot, dry conditions.

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15.4 Climatic Tipping Elements

Different parts of the Earth system exhibit *critical thresholds*, sometimes called "tipping points" (e.g., Lenton et al. 2008;[10] Collins et al. 2013;[25] NRC 2013;[33] Kopp et al. 2016[11]). These parts, known as *tipping elements*, have the potential to enter into self-amplifying cycles that commit them to shifting from their current state into a new state: for example, from one in which the summer Arctic Ocean is covered by ice, to one in which it is ice-free. In some potential tipping elements, these state shifts occur abruptly; in others, the commitment to a state shift may occur rapidly, but the state shift itself may take decades, centuries, or even millennia to play out. Often the forcing that commits a tipping element to a shift in state is unknown. Sometimes, it is even unclear whether a proposed tipping element actually exhibits tipping behavior. Through a combination of physical modeling, paleoclimate observations, and expert elicitations, scientists have identified a number of possible tipping elements in atmosphere–ocean circulation, the cryosphere, the carbon cycle, and ecosystems (Figure 15.1, left; Table 15.1).

Table 15.1: Potential tipping elements (adapted from Kopp et al. 2016[11]).

Candidate Climatic Tipping Element	State Shift	Main Impact Pathways
Atmosphere–ocean circulation		
Atlantic meridional overturning circulation	Major reduction in strength	Regional temperature and precipitation; global mean temperature; regional sea level
El Niño–Southern Oscillation	Increase in amplitude	Regional temperature and precipitation
Equatorial atmospheric superrotation	Initiation	Cloud cover; climate sensitivity
Regional North Atlantic Ocean convection	Major reduction in strength	Regional temperature and precipitation
Cryosphere		
Antarctic Ice Sheet	Major decrease in ice volume	Sea level; albedo; freshwater forcing on ocean circulation
Arctic sea ice	Major decrease in summertime and/or perennial area	Regional temperature and precipitation; albedo
Greenland Ice Sheet	Major decrease in ice volume	Sea level; albedo; freshwater forcing on ocean circulation
Carbon cycle		
Methane hydrates	Massive release of carbon	Greenhouse gas emissions
Permafrost carbon	Massive release of carbon	Greenhouse gas emissions
Ecosystem		
Amazon rainforest	Dieback, transition to grasslands	Greenhouse gas emissions; biodiversity
Boreal forest	Dieback, transition to grasslands	Greenhouse gas emissions; albedo; biodiversity
Coral reefs	Die-off	Biodiversity

One important tipping element is the Atlantic meridional overturning circulation (AMOC), a major component of global ocean circulation. Driven by the sinking of cold, dense water in the North Atlantic near Greenland, its strength is projected to decrease with warming due to freshwater input from increased precipitation, glacial melt, and melt of the Greenland Ice Sheet (see also discussion in Ch. 11: Arctic Changes).[34] A decrease in AMOC strength is probable and may already be culpable for the "warming hole" observed in the North Atlantic,[34, 35] although it is still unclear whether this decrease represents a forced change or internal variability.[36] Given sufficient freshwater input, there is even the possibility of complete AMOC collapse. Most models do not predict such a collapse in the 21st century,[33] although one study that used observations to bias-correct climate model simulations found that CO_2 concentrations of 700 ppm led to a AMOC collapse within 300 years.[37]

A slowing or collapse of the AMOC would have several consequences for the United States. A decrease in AMOC strength would accelerate sea level rise off the northeastern United States,[38] while a full collapse could result in as much as approximately 1.6 feet (0.5 m) of regional sea level rise,[39, 40] as well as a cooling of approximately 0°–4°F (0°–2°C) over the country.[37, 41] These changes would occur in addition to preexisting global and regional sea level and temperature change. A slowdown of the AMOC would also lead to a reduction of ocean carbon dioxide uptake, and thus an acceleration of global-scale warming.[42]

Another tipping element is the atmospheric–oceanic circulation of the equatorial Pacific that, through a set of feedbacks, drives the state shifts of the El Niño–Southern Oscillation. This is an example of a tipping element that already shifts on a sub-decadal, interannual timescale, primarily in response to internal noise. Climate model experiments suggest that warming will reduce the threshold needed to trigger extremely strong El Niño and La Niña events.[43, 44] As evident from recent El Niño and La Niña events, such a shift would negatively impact many regions and sectors across the United States (for more on ENSO impacts, see Ch. 5: Circulation and Variability).

A third potential tipping element is arctic sea ice, which may exhibit abrupt state shifts into summer ice-free or year-round ice-free states.[45, 46] As discussed above, climate models have historically underestimated the rate of arctic sea ice loss. This is likely due to insufficient representation of critical positive feedbacks in models. Such feedbacks could include: greater high-latitude storminess and ocean wave penetration as sea ice declines; more northerly incursions of warm air and water; melting associated with increasing water vapor; loss of multiyear ice; and albedo decreases on the sea ice surface (e.g., Schröder et al. 2014;[7] Asplin et al. 2012;[8] Perovich et al. 2008[9]). At the same time, however, the point at which the threshold for an abrupt shift would be crossed also depends on the role of natural variability in a changing system; the relative importance of potential stabilizing negative feedbacks, such as more efficient heat transfer from the ocean to the atmosphere in fall and winter as sea declines; and how sea ice in other seasons, as well as the climate system more generally, responds once the first "ice-free" summer occurs (e.g., Ding et al. 2017[47]). It is also possible that summer sea ice may not abruptly collapse, but instead respond in a manner proportional to the increase in temperature.[48, 49, 50, 51] Moreover, an abrupt decrease in winter sea ice may result simply as the gradual warming of Arctic Ocean causes it to cross a critical temperature for ice formation, rather than from self-reinforcing cycles.[52]

Two possible tipping elements in the carbon cycle also lie in the Arctic. The first is buried in the permafrost, which contains an estimated 1,300–1,600 GtC (see also Ch. 11: Arctic Changes).[53] As the Arctic warms, about 5–15% is estimated to be vulnerable to release in this century.[53] Locally, the heat produced by the decomposition of organic carbon could serve as a positive feedback, accelerating carbon release.[54] However, the release of permafrost carbon, as well as whether that carbon is initially released as CO_2 or as the more potent greenhouse gas CH_4, is limited by many factors, including the freeze–thaw cycle, the rate with which heat diffuses into the permafrost, the potential for organisms to cycle permafrost carbon into new biomass, and oxygen availability. Though the release of permafrost carbon would probably not be fast enough to trigger a runaway self-amplifying cycle leading to a permafrost-free Arctic,[53] it still has the potential to significantly amplify both local and global warming, reduce the budget of human-caused CO_2 emissions consistent with global temperature targets, and drive continued warming even if human-caused emissions stopped altogether.[55, 56]

The second possible arctic carbon cycle tipping element is the reservoir of methane hydrates frozen into the sediments of continental shelves of the Arctic Ocean (see also Ch. 11: Arctic Changes). There is an estimated 500 to 3,000 GtC in methane hydrates,[57, 58, 59] with a most recent estimate of 1,800 GtC (equivalently, 2,400 Gt CH_4).[60] If released as methane rather than CO_2, this would be equivalent to about 82,000 Gt CO_2 using a global warming potential of 34.[61] While the existence of this reservoir has been known and discussed for several decades (e.g., Kvenvolden 1988[62]), only recently has it been hypothesized that warming bottom water temperatures may destabilize the hydrates over timescales shorter than millennia, leading to their release into the water column and eventually the atmosphere (e.g., Archer 2007;[57] Kretschmer et al. 2015[63]). Recent measurements of the release of methane from these sediments in summer find that, while methane hydrates on the continental shelf and upper slope are undergoing dissociation, the resulting emissions are not reaching the ocean surface in sufficient quantity to affect the atmospheric methane budget significantly, if at all.[60, 64] Estimates of plausible hydrate releases to the atmosphere over the next century are only a fraction of present-day anthropogenic methane emissions.[60, 63, 65]

These estimates of future emissions from permafrost and hydrates, however, neglect the possibility that humans may insert themselves into the physical feedback systems. With an estimated 53% of global fossil fuel reserves in the Arctic becoming increasingly accessible in a warmer world,[66] the risks associated with this carbon being extracted and burned, further exacerbating the influence of humans on global climate, are evident.[67, 68] Of less concern but still relevant, arctic ocean waters themselves are a source of methane, which could increase as sea ice decreases.[69]

The Antarctic and Greenland Ice Sheets are clear tipping elements. The Greenland Ice Sheet exhibits multiple stable states as a result of feedbacks involving the elevation of the ice sheet, atmosphere-ocean-sea ice dynamics, and albedo.[70, 71, 72, 73] At least one study suggests that warming of 2.9°F (1.6°C) above a preindustrial baseline could commit Greenland to an 85% reduction in ice volume and a 20 foot (6 m) contribution to global mean sea level over millennia.[71] One 10,000-year modeling study[74] suggests that following the higher RCP8.5 scenario (see Ch. 4: Projections) over the 21st century would lead to complete loss of the Greenland Ice Sheet over 6,000 years.

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In Antarctica, the amount of ice that sits on bedrock below sea level is enough to raise global mean sea level by 75.5 feet (23 m).[75] This ice is vulnerable to collapse over centuries to millennia due to a range of feedbacks involving ocean-ice sheet-bedrock interactions.[74, 76, 77, 78, 79, 80] Observational evidence suggests that ice dynamics already in progress have committed the planet to as much as 3.9 feet (1.2 m) worth of sea level rise from the West Antarctic Ice Sheet alone, although that amount is projected to occur over the course of many centuries.[81, 82] Plausible physical modeling indicates that, under the higher RCP8.5 scenario, Antarctic ice could contribute 3.3 feet (1 m) or more to global mean sea level over the remainder of this century,[83] with some authors arguing that rates of change could be even faster.[84] Over 10,000 years, one modeling study suggests that 3.6°F (2°C) of sustained warming could lead to about 70 feet (25 m) of global mean sea level rise from Antarctica alone.[74]

Finally, tipping elements also exist in large-scale ecosystems. For example, boreal forests such as those in southern Alaska may expand northward in response to arctic warming. Because forests are darker than the tundra they replace, their expansion amplifies regional warming, which in turn accelerates their expansion.[85] As another example, coral reef ecosystems, such as those in Florida, are maintained by stabilizing ecological feedbacks among corals, coralline red algae, and grazing fish and invertebrates. However, these stabilizing feedbacks can be undermined by warming, increased risk of bleaching events, spread of disease, and ocean acidification, leading to abrupt reef collapse.[86] More generally, many ecosystems can undergo rapid regime shifts in response to a range of stressors, including climate change (e.g., Scheffer et al. 2001;[87] Folke et al. 2004[88]).

15.5 Paleoclimatic Hints of Additional Potential Surprises

The paleoclimatic record provides evidence for additional state shifts whose driving mechanisms are as yet poorly understood. As mentioned, global climate models tend to underestimate both the magnitude of global mean warming in response to higher CO_2 levels as well as its amplification at high latitudes, compared to reconstructions of temperature and CO_2 from the geological record. Three case studies—all periods well predating the first appearance of *Homo sapiens* around 200,000 years ago[89]—illustrate the limitations of current scientific understanding in capturing the full range of self-reinforcing cycles that operate within the Earth system, particularly over millennial time scales.

The first of these, the late Pliocene, occurred about 3.6 to 2.6 million years ago. Climate model simulations for this period systematically underestimate warming north of 30°N.[90] During the second of these, the middle Miocene (about 17–14.5 million years ago), models also fail to simultaneously replicate global mean temperature—estimated from proxies to be approximately 14° ± 4°F (8° ± 2°C) warmer than preindustrial—and the approximately 40% reduction in the pole-to-equator temperature gradient relative to today.[91] Although about one-third of the global mean temperature increase during the Miocene can be attributed to changes in geography and vegetation, geological proxies indicate CO_2 concentrations of around 400 ppm,[91, 92] similar to today. This suggests the possibility of as yet unmodeled feedbacks, perhaps related to a significant change in the vertical distribution of heat in the tropical ocean.[93]

The last of these case studies, the early Eocene, occurred about 56–48 million years ago. This period is characterized by the absence of permanent land ice, CO_2 concentrations peaking

around 1,400 ± 470 ppm,[94] and global temperatures about 25°F ± 5°F (14°C ± 3°C) warmer than the preindustrial.[95] Like the late Pliocene and the middle Miocene, this period also exhibits about half the pole-to-equator temperature gradient of today.[15, 96] About one-third of the temperature difference is attributable to changes in geography, vegetation, and ice sheet coverage.[95] However, to reproduce both the elevated global mean temperature and the reduced pole-to-equator temperature gradient, climate models would require CO_2 concentrations that exceed those indicated by the proxy record by two to five times[15]—suggesting once again the presence of as yet poorly understood processes and feedbacks.

One possible explanation for this discrepancy is a planetary state shift that, above a particular CO_2 threshold, leads to a significant increase in the sensitivity of the climate to CO_2. Paleo-data for the last 800,000 years suggest a gradual increase in climate sensitivity with global mean temperature over glacial-interglacial cycles,[97, 98] although these results are based on a time period with CO_2 concentrations lower than today. At higher CO_2 levels, one modeling study[95] suggests that an abrupt change in atmospheric circulation (the onset of equatorial atmospheric superrotation) between 1,120 and 2,240 ppm CO_2 could lead to a reduction in cloudiness and an approximate doubling of climate sensitivity. However, the critical threshold for such a transition is poorly constrained. If it occurred in the past at a lower CO_2 level, it might explain the Eocene discrepancy and potentially also the Miocene discrepancy: but in that case, it could also pose a plausible threat within the 21st century under the higher RCP8.5 scenario.

Regardless of the particular mechanism, the systematic paleoclimatic model-data mismatch for past warm climates suggests that climate models are omitting at least one, and probably more, processes crucial to future warming, especially in polar regions. For this reason, future changes outside the range projected by climate models cannot be ruled out, and climate models are more likely to underestimate than to overestimate the amount of long-term future change.

TRACEABLE ACCOUNTS

Key Finding 1

Positive feedbacks (self-reinforcing cycles) within the climate system have the potential to accelerate human-induced climate change and even shift the Earth's climate system, in part or in whole, into new states that are very different from those experienced in the recent past (for example, ones with greatly diminished ice sheets or different large-scale patterns of atmosphere or ocean circulation). Some feedbacks and potential state shifts can be modeled and quantified; others can be modeled or identified but not quantified; and some are probably still unknown. (*Very high confidence* in the potential for state shifts and in the incompleteness of knowledge about feedbacks and potential state shifts).

Description of evidence base

This key finding is based on a large body of scientific literature recently summarized by Lenton et al.,[10] NRC,[33] and Kopp et al.[11] As NRC[33] (page vii) states, "A study of Earth's climate history suggests the inevitability of 'tipping points'—thresholds beyond which major and rapid changes occur when crossed—that lead to abrupt changes in the climate system" and (page xi), "Can all tipping points be foreseen? Probably not. Some will have no precursors, or may be triggered by naturally occurring variability in the climate system. Some will be difficult to detect, clearly visible only after they have been crossed and an abrupt change becomes inevitable." As IPCC AR5 WG1 Chapter 12, section 12.5.5[25] further states, "A number of components or phenomena within the Earth system have been proposed as potentially possessing critical thresholds (sometimes referred to as tipping points) beyond which abrupt or nonlinear transitions to a different state ensues." Collins et al.[25] further summarizes critical thresholds that can be modeled and others that can only be identified.

Major uncertainties

The largest uncertainties are 1) whether proposed tipping elements actually undergo critical transitions; 2) the magnitude and timing of forcing that will be required to initiate critical transitions in tipping elements; 3) the speed of the transition once it has been triggered; 4) the characteristics of the new state that results from such transition; and 5) the potential for new tipping elements to exist that are yet unknown.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is *very high confidence* in the likelihood of the existence of positive feedbacks, and the tipping elements statement is based on a large body of literature published over the last 25 years that draws from basic physics, observations, paleoclimate data, and modeling.

There is *very high confidence* that some feedbacks can be quantified, others are known but cannot be quantified, and others may yet exist that are currently unknown.

Summary sentence or paragraph that integrates the above information

The key finding is based on NRC[33] and IPCC AR5 WG1 Chapter 12 section 12.5.5,[25] which made a thorough assessment of the relevant literature.

Key Finding 2

The physical and socioeconomic impacts of compound extreme events (such as simultaneous heat and drought, wildfires associated with hot and dry conditions, or flooding associated with high precipitation on top of snow or waterlogged ground) can be greater than the sum of the parts (*very high confidence*). Few analyses consider the spatial or temporal correlation between extreme events.

Description of evidence base

This key finding is based on a large body of scientific literature summarized in the 2012 IPCC Special Report on Extremes.[23] The report's Summary for Policymakers (page 6) states, "exposure and vulnerability are key determinants of disaster risk and of impacts when risk is realized... extreme impacts on human, ecological, or physical systems can result from individual extreme weather or climate events. Extreme impacts can also result from non-extreme events where exposure and vulnerability are high or from a compounding of events or their impacts. For example, drought, coupled with extreme heat and low humidity, can increase the risk of wildfire."

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Major uncertainties

The largest uncertainties are in the temporal congruence of the events and the compounding nature of their impacts.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is *very high confidence* that the impacts of multiple events could exceed the sum of the impacts of events occurring individually.

Summary sentence or paragraph that integrates the above information

The key finding is based on the 2012 IPCC SREX report, particularly section 3.1.3 on compound or multiple events, which presents a thorough assessment of the relevant literature.

Key Finding 3

While climate models incorporate important climate processes that can be well quantified, they do not include all of the processes that can contribute to feedbacks, compound extreme events, and abrupt and/or irreversible changes. For this reason, future changes outside the range projected by climate models cannot be ruled out (*very high confidence*). Moreover, the systematic tendency of climate models to underestimate temperature change during warm paleoclimates suggests that climate models are more likely to underestimate than to overestimate the amount of long-term future change (*medium confidence*).

Description of evidence base

This key finding is based on the conclusions of IPCC AR5 WG1,[99] specifically Chapter 9;[1] the state of the art of global models is briefly summarized in Chapter 4: Projections of this report. The second half of this key finding is based upon the tendency of global climate models to underestimate, relative to geological reconstructions, the magnitude of both long-term global mean warming and the amplification of warming at high latitudes in past warm climates (e.g., Salzmann et al. 2013;[90] Goldner et al. 2014;[91] Caballeo and Huber 2013;[95] Lunt et al. 2012[15]).

Major uncertainties

The largest uncertainties are structural: are the models including all the important components and relationships necessary to model the feedbacks and if so, are these correctly represented in the models?

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is *very high confidence* that the models are incomplete representations of the real world; and there is *medium confidence* that their tendency is to under- rather than over-estimate the amount of long-term future change.

Summary sentence or paragraph that integrates the above information

The key finding is based on the IPCC AR5 WG1 Chapter 9,[1] as well as systematic paleoclimatic model/data comparisons.

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